Michael Faraday and the Physics of 100 Years Ago

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Michael Faraday was born on 22 September 1791, in Newington, Surrey, near London. His father, a journeyman blacksmith, had left the North-country to try to better his lot in the metropolis as a depression gradually settled over England. His mother had worked as a maidservant before her marriage to James Faraday and had already borne her husband a daughter, Elizabeth, and a son, Robert. A second daughter, Margaret, soon followed Michael. The family was desperately poor. James Faraday was in almost constant ill health and could work only sporadically. As prices rose as a result of England's involvement in the French Revolutionary Wars, simple subsistence became a major problem. In later years Faraday told of having been given a single loaf of bread which was to serve him as his main course for a week.

What sustained the Faradays throughout their hardships was a simple but extraordinarily powerful religious faith. James Faraday was a Sandemanian. The Sandemanian Church rejected what it considered to be all the false trappings of the Church of England and sought to recapture both the letter and the spirit of the early Church. The congregation was a true brotherhood in which all helped one another both materially and spiritually. Life within the Sandemanian community was often hard, but it was never desperate. With the exception of the influence of his family, about which we know very little, the Sandemanian Church was the most important factor in Michael Faraday's education. It was at a church "school" that he learned the three R's—the total extent of his formal education. More importantly, the Sandemanian religion provided him with two convictions that were essential elements of his later scientific career. According to Judeo-Christian tradition, the universe was, literally, made for man. The philosophical result of this view is the belief in final causes which, as innumerable science texts assure us, was banished from science by the Scientific Revolution. They were not banished from Faraday's mind. He had a deep conviction of the ultimate harmony of the world which led him onward in his physical pursuits. This harmony, he also believed, was designed for man's well-being. Thus he could state at the end of a lecture on ozone in 1859 (*1*, p. 103):

> These are the glimmerings we have of what we are pleased to call the *second causes* by which the *one Great Cause* works his wonders and governs this earth. We flattered ourselves we knew what air was composed of, and now we discover a *new* property which is imponderable, and invisible, except through its *effects* which I shewed you in the last experiment; but while it fades the ribbon, it gives the glow of health to the cheek, and is just as necessary for the good of mankind, as the other parts of which air is composed.

From his religion Faraday also drew a deep and profound sense of his own (and everyone else's) fallibility. He *knew* that he must err and accepted this as a simple fact. He would do his utmost to minimize his errors—he would repeat his experiments hundreds of times; he would scrutinize them with the most critical eye; he would check and recheck his arguments. But he would not insist upon them, once pub-

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lished. If others challenged his results or his ideas, he refused to be drawn into controversy except insofar as he was willing to clarify his sometimes obscure language. Thus, in Faraday's scientific career there is none of the acerbity, belligerence, and intransigence that marked the careers of such contemporaries as Liebig and Tyndall. The truth (always with a small *t*), he felt, would ultimately emerge from the critical interplay of ideas without noisy advocacy.

The young Faraday experienced these religious influences in a world far removed from the world of science. At the age of 14 he was apprenticed to a bookbinder and seemed destined to lead the life of an ordinary tradesman in London. Then, his passion for science was aroused by reading the article on electricity in a volume of the *Encyclopaedia Britannica* brought into his master's shop to be bound. Still, he might have remained a slightly unusual bookbinder had he not been brought to Sir Humphry Davy's attention and, through a series of fortuitous circumstances, hired as Davy's assistant at the Royal Institution in 1813. Thus began his apprenticeship as a chemist.

The Foundations

Under Davy's tutelage Faraday rapidly assimilated the chemical knowledge of the day. More important than the mere digestion of facts, however, was the theoretical point of view he received from his famous mentor. Davy himself had lived through a personal "scientific revolution" in his youth and was able to pass on its meaning to his disciple.

At the end of the 18th and the beginning of the 19th centuries the nature of physical science underwent an important and fundamental change. By and large, the Newtonian breakthrough of the 17th century had focused the attention of physicists primarily upon the physics of the observable world. The publication of the *Mécanique analytique,* by Lagrange, in 1788 marked the culmination of the development of terrestrial mechanics in the 18th century. The appearance of the thick quartos of the *Mécanique céleste* of Pierre Simon de Laplace in the early years of the 19th century left no doubt of the ability of the Newtonian principles of natural philosophy to deal with celestial phenomena. By the time Faraday began his active career as a scientist, the realm of macrophysics seemed pretty well under the control of the physicist.

The triumphs of Newtonian physics also served to lay out, more or less implicitly, the rules of the game. In macrophysics, certain fundamental aspects were given. If one attacked the problem of the equilibrium of a number of heavy bodies suspended by ropes from pulleys, there was no need to worry about the reality of these bodies. They were simply there, and could be represented by their weight or by the force of gravity acting upon them. It was permissible, indeed necessary, to make certain simplifying assumptions —such as frictionless pulleys, inextensible ropes, and the concentration of mass at the center of gravity—in order to write the mathematical equations by means of which the situation could be analyzed. Similarly, in celestial mechanics, the real existence of the celestial bodies themselves was never in doubt. They were the centers of the gravitational forces which were the objects of Laplace's analysis. Thus, subtly and almost imperceptibly, there were introduced into physics certain ideas and attitudes which, in the 19th century, had almost the strength of dogma. Force, for example, was always associated with body in macrophysics. Hence, wherever force appeared, it seemed only reasonable to assume the existence of a body, even if no body were perceptible. In macrophysics, all forces were central forces, acting at a distance, between the reacting bodies. All forces, then, must be central forces, acting at a distance between the centers of gravity of the bodies from which these forces arose. Finally, the success of the application of mathematics to macrophysics led to the widespread feeling that mathematical representation was the essence of all physics. If a physical hypothesis could not be put in mathematical terms, then the chances were very high that it was a false one.

With the solution of the major problems of macrophysics, the 19th-century physicist turned to an area which had been relatively neglected by the physicists of the 18th century. Although Newton had thrown out many helpful hints on the way to approach microphysics, this field had been cultivated largely by chemists. Some of them had learned some very important lessons from their failure to achieve dramatic breakthroughs like those made by their physicist friends. By the time the physicist became seriously interested in such topics as light, heat, electricity, magnetism, and molecular forces, some chemists were on the verge of rejecting the foundations which had served so well to uphold the edifice of macrophysics. Fortunately for Faraday, Davy was one of these chemists.

The Corpuscular System

The basic point at issue was that of the origin of force. In macrophysics, force was considered an essential quality of body. The weight of an object was clearly to be associated with the object, just as the gravitational force of the sun obviously had its origin in the sun. Thus, in microphysics, it seemed only natural to assume that the presence of a force necessarily implied the existence of some material body from which the force emanated. Although it was possible for the same body to be the seat of different kinds of force, it seemed simpler to assume different bodies for each specifically different force. By the beginning of the 19th century, certain "forces" were known that could be studied in the laboratory—light, heat, electricity, and magnetism. Each force, it was thought, originated in a specific kind of body. Light, as Sir Isaac Newton had strongly implied, was composed of corpuscles of different sizes, hence the different colors. The particles of heat, or "caloric," were mutually repulsive, and this explained their ability to cause ordinary objects to expand when the caloric content was increased. Most physicists on the Continent believed that the positive and negative aspects of electricity and the boreal and austral forces of magnetism required separate corpuscles. Hence, corpuscles of positive electricity, negative electricity, boreal magnetism, and austral magnetism were conceived as the underlying material basis for electrical and magnetic phenomena. If one adds to these "imponderable" substances the atoms of ordinary matter, whose relative weights John Dalton determined in the first decade of the 19th century, the picture is complete.

To the casual observer, there was a wonderful simplicity in this system. Seven "elementary" particles made up the totality of reality. Of these seven, five—positive electricity, negative electricity, boreal magnetism, austral magnetism, and ponderable matter—obeyed the Newtonian inverse-square law. The

only mysteries left for the generation that followed Laplace were the force laws of action of light and of caloric. Otherwise, the future task of physics was that of devising more refined methods of mathematical computation so that the results of the interaction of the "elementary" particles could be calculated to the desired degree of accuracy.

Objections

This microphysical world appealed to many—especially to the mathematical physicist. But it also repelled many, among whom were some of the leading chemists of the day. To mathematical illiterates like Sir Humphry Davy, elegant equations were so much gibberish. Even had he understood them, it is doubtful that Davy would have been seduced by them; for they gave no real aid in understanding the specific interactions with which the chemist was concerned. Given the atomic weights of nitrogen, sulfur, and chlorine, for example, could the physicist provide any insight into their possible chemical combinations? Could he even predict whether they would react or simply coexist in a flask forever as nitrogen, sulfur, and chlorine?

The corpuscular system was less than seductive to the chemist for another reason. The mathematical physicist, in his mind's eye, could see the trajectories of the ultimate particles and the differential equations associated with them. Each particle had its own, personal, equation; particulate interactions involved the association of these equations. To the chemist, all seven kinds of particles were necessarily associated. For example, for a chemist, an atom of iron contained a central ponderable atom, an atmosphere of caloric (for caloric could be squeezed out of an iron bar by pounding it), an atmosphere of light (the iron will glow when hit long enough), positive and negative electricity (the voltaic current will decompose iron salts in solution), and austral and boreal magnetism. The simplicity of the corpuscular model disappears when the ultimate particles are forced into the union demanded by chemistry.

Beyond these purely chemical objections there were, as well, certain methodological aspects which could upset the thoughtful. The aim of macrophysics was to reduce observable phenomena to mathematical description. In macrophysics, the number of purely physical assumptions necessary to accomplish this could be kept to a minimum through accurate and direct observation. The Newtonian assumption that the *r* in the inverse-square law of gravitation should be the distance between the centers, rather than between the superficies, of two gravitating bodies could be not only proved mathematically but easily checked by observation. In the microphysical realm, hypothetical actions were not so easily evaluated. One case may serve to illustrate this. In 1820, Augustin Fresnel pointed out to Ampère that the circular electrical currents which Ampère felt must exist in permanent magnets could not be ordinary currents concentric with the axis of the magnet. If such currents existed, they should be detectable by their heating effect, but a magnet was not warmer than its surroundings. But, argued Fresnel, the same results could be obtained if electrical currents were assumed to circulate around the molecules of the magnet. The fact that molecular electrical currents did not generate heat did not perturb Fresnel for, as he put it *(2)*, "our ideas on the constitution of bodies are too incomplete for us to know whether electricity ought to produce heat in this case." In short, on the molecular level, anything goes. Ad hoc hypotheses could be framed almost without limit so long as they offered a means of explaining physical phenomena or provided a basis for mathematical analysis.

One final aspect of the corpuscular universe should be noted, for it contributed to the opposition to it that arose in the early 19th century. In the hands of an ardent proponent like Laplace, this system of the world was overtly, even defiantly, materialistic, deterministic, and atheistic. Following hard on the heels of the French Revolution, this system was strongly tinged with political and social subversion. There were many, particularly in England, who felt that the great cataclysm of 1789 had been caused by precisely those ideas which Laplace and his followers now asserted to be the necessary foundations of physics. Any alternative system which avoided materialism and atheism would be eagerly accepted, provided, of course, it also proved useful in the pursuit of scientific truth. In the early years of the 19th century such a system was promulgated in England, and both Davy and Faraday were strongly influenced by it.

The System of Forces

In 1799, Samuel Taylor Coleridge, the poet and literary critic, returned from a year's journey to Germany filled with enthusiasm for the new Kantian metaphysics. He was especially impressed with the dismissal of atomism by some of Kant's disciples and the substitution of forces as the basic phenomenal reality of the world. After all, we do not directly experience atoms or the other theoretical entities of microphysics. What we observe and measure and probe are the forces with which these hypothetical corpuscles are endowed. Why not, then, do away with the material substratum entirely and consider forces to be the ultimate reality? There were a number of advantages to this approach. For Coleridge, the important thing was that it removed the duality of matter and spirit and permitted God, once again, to become a living presence in the world. For the natural philosopher, it simplified matters considerably. If force were the ultimate reality, then only the two forces of attraction and repulsion existed. The appearance of these forces as electrical and magnetic attractions and repulsions, thermal expansion, chemical affinity, and so on, depended upon the conditions under which the basic forces manifested themselves. The seven elementary particles of Laplacian physics could be replaced by two forces. Furthermore, predictions could be made of new effects which found no place in the Laplacian system. One would not, for example, expect the conversion of one *particle* into another; electricity was electricity and magnetism was magnetism and, while the two kinds of particles might interact, there was no reason to anticipate the *production* of magnetism by the electrical particles, or vice versa. If all observable forces, however, were but manifestations of attraction and repulsion under different conditions, then it was logical to assume the conversion of one force into another when the proper conditions were present. It was this logic that guided Hans Christian Oersted in his 20-year quest for the magnetic effect of an electric current.

One of Coleridge's best friends was Humphry Davy, himself a poet and ardent student of philosophy. Even before Coleridge returned to England, Davy's own questing mind had led him to a point where he could be only favorably impressed by the philosophi-

cal news from Germany. In April 1799, Davy had written to his friend and patron Davies Gilbert (*1*, p. 67): "The supposition of active powers common to all matter, from the different modifications of which all the phenomena of its changes result, appear to me more reasonable than the assumption of certain imaginary fluids alone endowed with active powers, and bearing the same relation to common matter, as the vulgar philosophy supposes spirit to bear to matter." It should be noted that, in the face of public criticism, Davy steadfastly refused to use the Laplacian language of imponderable fluids and spoke, instead, of the powers and energies of matter.

The system of forces was certainly seductive, but it, too, involved certain difficulties. For the physicist, it offered a considerable simplification of the basic hypotheses of his science, but, for the chemist, it was also a source of specifically chemical difficulties. The conversions of the two basic forces offered little to the man interested in the singular qualities of the chemical elements. Given the view that chemical affinity and electricity, for example, were somehow connected, to what did one appeal for an understanding of the specific chemical differences between sodium, potassium, and chlorine? There was no place for such singularities within the physics of forces. Once again, it would appear to be Davy who saw the way to reconcile the system of forces with another system in which chemical singularities could exist. In the 18th century an atomic theory had been formulated by Father Roger Joseph Boscovich, in which only forces figured. The atom was a mathematical point, surrounded by alternating zones of repulsive and attractive forces (Fig. 1). These "atoms," in combination with one another, made up the moleculae of the chemical elements. Chemical qualities were the result of the different patterns of force produced by the different combinations of the point atoms. Thus, even the most basic questions of the chemist could be answered in terms of forces, and, it should again be noted, forces were not hypothetical but real. They were experimentally determinable facts, not metaphysical hypotheses. To someone who was suspicious of hypotheses, except insofar as they suggested experiments, the system of force and of point atoms had a clear advantage over that of material particles. If to this scientific superiority is added a religious dimension, the advantage becomes compelling.

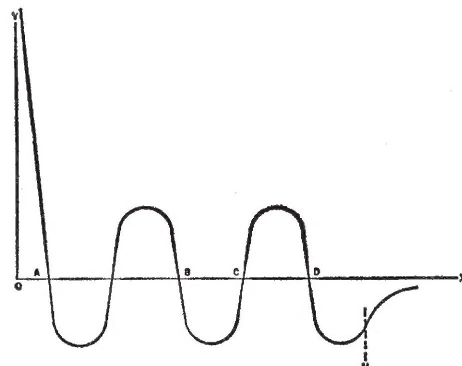

Fig. 1. The Boscovichean point atom has its center at *O*. The *x*-axis represents the distance from this mathematical point. The part of the curve above the *x*-axis represents repulsive force; the part below the *x*-axis, attractive force. If a test particle is brought in from infinity, it will follow the hyperbola required by the inverse-square law until it reaches some microscopic distance such as that indicated at *H*. The attractive force then varies in accordance with the curve, turning into a repulsive force at *D*, back to an attractive force at *C*, and so on. Between *A* and *OY*, the relationship between the *y*-axis and the curve representing the repulsive force becomes asymptotic, thus the property of impenetrability for the point atom is preserved.

Faraday was aware of all these factors. In his early years as an apprentice chemist he refused to commit himself to any system, simply suspending judgment on the nature of ultimate reality. But, as he delved deeper into the nature of matter and force, the system of forces and point atoms gradually received his allegiance until, by the 1830's, his theoretical ideas were consistently expressed in its terms. Not until the 1850's did he abandon some of its tenets to rise to a height of abstraction unmatched by any of his contemporaries.

The Transmission of Force

Faraday's first scientific paper, "Analysis of Native Caustic Lime of Tuscany," was published in 1816 and was followed in the next 5 years by papers of a similar nature. It was as an analytical chemist that he discovered and described benzene, in 1825. His intense interest in electricity and magnetism was aroused in the spring of 1821, when his friend Richard Phillips, editor of the *Annals of Philosophy*, asked him to write a history of the new field of electromagnetism. Hans Christian Oersted's announcement of the magnetic effect of an electric current, in the summer of 1820, had touched off such a flurry of experiment and theorizing that many people were confused as to what actually did occur in the neighborhood of a current-carrying wire. Phillips knew that his friend would repeat the experiments, examine the theoretical systems built upon them, and give his readers a sober and critical account of both. What he did not know was that his simple request would lead to Faraday's first important discovery in electromagnetism and to a new concept of the transmission of force.

In September of 1821, Faraday suddenly realized that his experimental investigation of the magnetic effects to be found near a current-carrying wire led to a startling prediction. If a single magnetic pole were free to move, it would travel around the wire in a circle! He immediately devised a simple apparatus to illustrate this effect and thus invented the first electric motor in which electrical force was converted into mechanical motion (Fig. 2).

The theoretical implications of his discovery were equally dramatic. The "pattern" of force around a current-carrying wire was obviously circular. To a man trained in classical, mathematical physics (as André-Marie Ampère was, for example), this fact had to be explained in terms of central forces acting in straight lines between some kind of current elements in both the wire and the magnetic detector. To Faraday, the experimental fact sufficed; the magnetic force *was* circular. He even went on to show how the attractions and repulsions of ordinary magnetic poles could be deduced from his circular line of magnetic force (Fig. 3). Thus, magnetic central forces were shown to be the resultant of the circular force. Faraday's total lack of mathematical training here stood him in good stead. Had he viewed physics as Laplace or Ampère did, he would have been forced (as Ampère was) to decompose his circular magnetic force into central forces and reduce electromagnetism to neat, Laplacian terms. Instead, he defended his circular force and thereby gave birth to the idea of the line of force, which was to be central to his thinking throughout his life. Central forces require no emphasis on the line of force: the line is always straight, connecting the centers of the two interacting bodies. The believer in

central forces also need not trouble himself with the mechanism of the interaction. By the 19th century, "action at a distance" was accepted by all but the most finicky physicists, and it seemed only logical to assume that this action had to be in straight lines. Faraday's line of force, however, by being curved, almost required a consideration of the mechanism of transmission of the force. If it were simply "action at a distance," the action certainly took the long way round in its manifestation. From 1821 on, Faraday was to agonize over the way in which force was transmitted. Out of his agony were to come his great discoveries.

Almost from the moment of his first discovery, Faraday thought of the electromagnetic force as a strain imposed upon the molecules of the surrounding medium. The theory of point atoms lent itself particularly well to this view, although Faraday did not, at this time, explicitly call upon it. The hypothesis of such an intermolecular strain did permit him to envision electromagnetic effects in a rather unorthodox way. Instead of assuming currents of positive and negative fluids passing by one another in some complex fashion, might it not be possible to explain the phenomena of electrodynamics in terms of the vibration of strained molecules? A current might be a wave passing down a wire; the magnetic effect of the wave was a state of tension induced in the surrounding medium by the wave. The ability of waves to transmit "force" without the transmission of an independent body in which the force was inherent had only recently been triumphantly demonstrated in Fresnel's theory of the undulatory nature of light. Why should not electricity act in the same way?

Electromagnetic Induction

This appears to have been the thinking behind Faraday's famous induction-ring experiment of August 1831. He expected a momentary wave to pass through the primary coil. The magnetic effects would be intensified by the iron ring and, thereby, react upon the secondary coil, producing a momentary current in it. What he did not expect was a second current in the secondary when the primary circuit was broken. Yet, this was not too surprising, after all, for if the first pulse of the electric "wave" set up a magnetic strain in the surrounding medium, then the momentary current in the secondary marked the creation of the strain. The collapse of the strain, it could be argued, should be indicated by another momentary current, in the opposite direction. In between, the medium must exist in a state of constant strain, and Faraday christened this condition the electrotonic state. The embarrassing thing about this state to Faraday, the experimentalist, was the fact that it was totally indetectable! In 1822 Faraday had attempted to detect a strain in a decomposing electrolytic solution by shining a ray of plane-polarized light through it to see if its plane was altered, but to no avail. Now, he tried other methods, but still could get no effect. He was convinced, however, that the electrotonic state must exist, and, over the years, he kept devising experimental tests for detecting it.

In 1831 his attention could not be allowed to wander far from his new discovery of electromagnetic induction. Immediately after this discovery he substituted a moving permanent magnet for the iron ring. Then, this effect was broadened by introducing a rotating circular copper disk between the poles of a permanent horseshoe magnet. In the *First Series of the Experimental Researches in Electricity* he reported the discovery of electromagnetic induction, the invention of the dynamo, and the law connecting the lines of force with the current generated. Not bad for a start!

A start was all it was, for Faraday realized the vast new territory he had opened up. But, as he pushed ahead, reporting his path in the *Second Series*, he became aware of the necessity of preparing a base camp from which further trips into the wilderness could begin.

Intermolecular Action

Faraday's discoveries had already stirred the speculative fancies of many who saw in the electromagnetic current a separate "fluid" to be added to

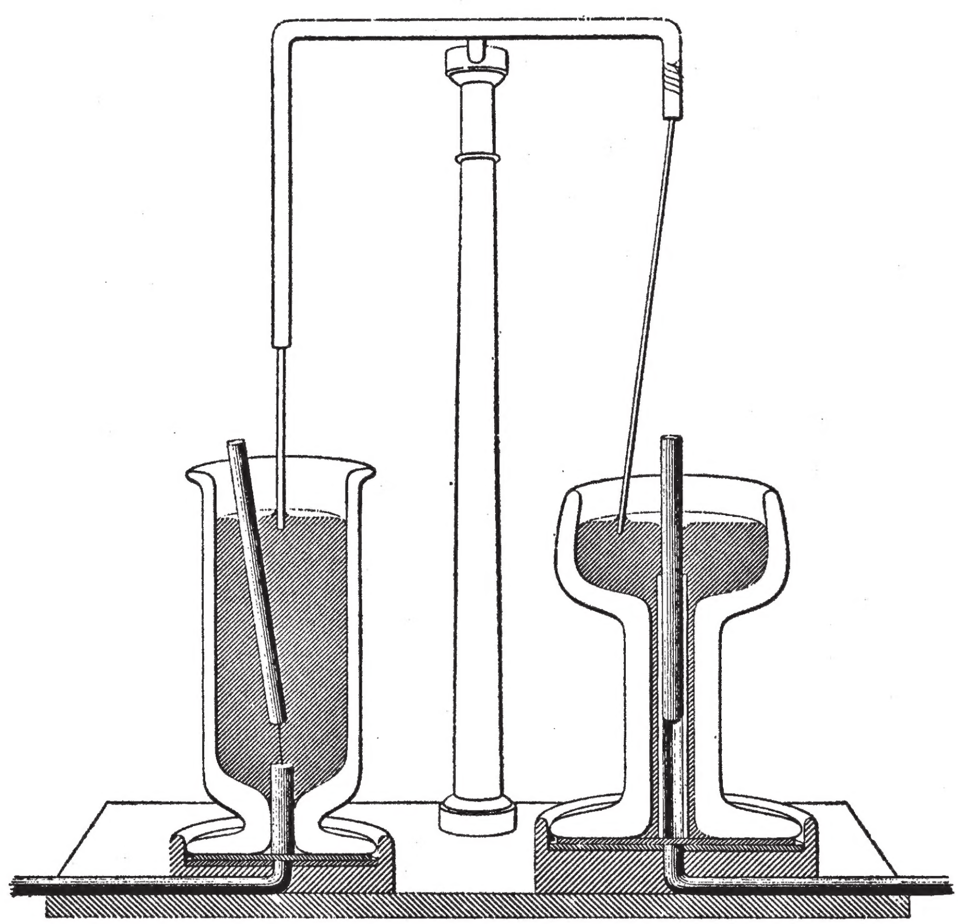

Fig. 2. Faraday's apparatus for illustrating electromagnetic rotation. At left, a cylindrical bar magnet, plunged into a beaker of mercury (which was part of the electrical circuit), rotated around the end of a current-carrying wire that made contact with the mercury. At right, the magnet was fixed and the wire was so mounted that it could turn about the point of suspension, and thus rotate around the magnetic pole.

the other imponderables. Faraday was intent upon reducing, not multiplying, the theoretical entities of his science, so he paused in 1832 to prove to himself and to his contemporaries that all electrical manifestations—electrostatic, electrodynamic, galvanic, animal, and thermoelectric—involved precisely the same force of nature. Faraday was particularly concerned to prove that electrostatic discharge could cause electrochemical decomposition, for there were those who insisted upon a separate galvanic fluid generated by the voltaic cell. It was in these experiments that Faraday was led to his famous two laws of electrolysis and to his discoveries in electrochemistry. More important, however, was his realization that electrochemical decomposition could take place without the presence of electrical poles. The older theories had viewed electrochemical decomposition as the action, at a distance, of the poles of the electrochemical cell upon the decomposing molecules. The poles were the centers from which this decomposing force emanated to tear the molecules apart. To Faraday's surprise, he found that decomposition took place when an electrostatic generator was discharged into the air *through* a piece of blotting paper soaked in potassium iodide. Here there were no poles; the mere passage of the electricity was sufficient. It was at this moment that Faraday conceived a daring thought. Perhaps the electrical forces did *not* act at a distance, as everyone since Franklin, or at least Coulomb, had assumed. Perhaps they were transmitted from particle to particle. Decomposition occurred when the interparticulate strain shifted the forces of chemical affinity from the constituents of one molecule to those of its neighbors on each side. The strain, then, would be accompanied by a physical migration of the molecular constituents without these constituents ever existing in the free state in the solution. This immediately solved a basic problem that had plagued Faraday's predecessors, for, if molecules were torn apart by the poles, why could the "fragments" not be detected by ordinary chemical means?

In his mind's eye Faraday could now picture the electrochemical lines of intermolecular strain. The volume of the molecules would necessarily make these lines curves. These curves accounted for the fact that electrochemical deposition upon the electrodes was uniform and not concentrated on the sides facing each other. The curves also looked suspiciously like magnetic lines of force, but Faraday was too excited over their implications for the theory of electricity to be drawn away into the theory of magnetism. What if *all* electrical action were intermolecular instead of action at a distance? To Faraday, and to physicists of his generation nourished upon the concept of action at a distance, such a heresy was almost unthinkable. Yet, there were precedents for it. As Faraday was to point out later, Newton himself had rejected action at a distance and, perhaps, all Faraday was doing was restoring physics to its proper Newtonian foundations. In any case, the idea of intermolecular action offered some intriguing possibilities for experiment, and Faraday was quick to exploit them.

Unified Theory of Electricity

We can deal with only one of them here, but it was a fundamental one for Faraday. For the orthodox physicist, the forces between two charged bodies depended solely upon the quantities of the charges and the distance between the two bodies. If the action, however, depended upon the transmission of electrostatic force by the molecules of the intervening medium, then the "amount" of force transmitted might bear some relation to the nature of these molecules. Thus Faraday was led to the discovery of specific inductive capacity which, like chemical affinity, bore a definite relation to the particles involved. But, it might be objected, where are these molecules *in vacuo* where electrostatic action still takes place? Point atoms, it should be remembered, are infinite, so the problem does not arise. Few of Faraday's contemporaries could see this, and most felt him to be completely muddled. He *was* muddled, for the forces of the point atoms *do* act at a distance, or, as Faraday saw them, simply *were* in space. Disturbance of these forces led to electrical phenomena. Upon this confused idea, Faraday constructed a unified theory of electricity. Insulators were bodies which could withstand a great deal of electrostatic strain; electrolytes were bodies whose "breaking point" was exactly determined by the chemical affinities of their constituents. The stronger the affinities were, the easier it was to distort the molecule and permit the transfer of partners (*3*). When the "slippage" took place, the strain was momentarily relaxed, only to be built up immediately again. This buildup and breakdown of strain constituted the electric "wave" or current. Good conductors would take up little strain, and so the buildup and breakdown were extremely rapid and the "wave" was easily generated and renewed.

In 1838, after 7 years of concentrated effort, Faraday presented this theory to the world. The relief of the mental strain under which he had labored for 7 years was too sudden and his intellectual faculties collapsed. From 1839 until 1845 he was able to work only fitfully between bouts of giddiness, headache, and loss of memory. His condition was not improved by the coolness with which his theory was received. It would take more than a host of experiments and fundamental discoveries to convince his orthodox brethren. What was needed was mathematics to make the theorists sit up and take notice. This Faraday was unable to provide.

Fortunately, there were some younger men in England to whom Faraday's ideas had the appeal of novelty and heterodoxy. The young William Thomson, later Lord Kelvin, was just testing his powers as a theorist in 1845 when he encountered Faraday's papers on electricity. Unlike his older contemporaries, he was attracted rather than repelled by Faraday's daring and sometimes incredible hypotheses of electrical action. Nothing would do but that he reduce Faraday's often obscure language to the purity and elegance of mathematics and *then* see what could be made of his theories. The results were reported to Faraday in a letter from Thomson dated 6 August 1845. Not only did Thomson take Faraday seriously, he was even able to suggest some consequences of Faraday's theory which might be capable of experimental verification. In particular, he suggested that a state of electrostatic tension ought to be detectable by plane-polarized light. The electrotonic state, then, did not exist solely in Faraday's imagination but was deducible from Thomson's mathematics.

Illumination of Lines of Force

With Thomson's analysis to spur him on, Faraday plunged back into his experimental search for the electrotonic state. It still resisted all his efforts to

detect it. Finally he abandoned the purely electrical road. Perhaps electrostatic forces were simply too feeble to produce a detectable effect. Magnetic forces, on the other hand, were something else again; where an electrostatically charged body could lift milligrams of chaff, a powerful electromagnet could hold hundredweights in its embrace. Furthermore, magnetic lines of force, like their electrostatic cousins, were curved, indicating to Faraday that the transmission of the magnetic force was likewise intermolecular. Might not a "magnetotonic" state be more easily detectable, then, than the electrotonic? Should not a transparent body placed in the powerful magnetic field between the poles of an electromagnet be strained? And should not this strain be detectable by polarized light? The experiment was tried, but with no effect. Faraday now was not to be put off by Nature's reluctance to reveal herself. The effect *must* exist! Air, flint glass, iceland spar—all were examined to no avail. Finally Faraday hit upon a piece of borate-of-lead glass of very high refractive index that he had made back in the 1820's for optical researches. The plane of the polarized light was now rotated sufficiently to be easily detected. The state of strain for which he had looked for so many years was now an experimental fact.

Yet, as was so often the case in Faraday's experimental investigations, more evidence was forthcoming than was necessary simply to prove the point he sought. The rotation of the plane of polarized light revealed a strain, but it was a peculiar kind of strain. The direction of the rotation depended *solely* upon the polarity of the magnetic field; the glass seemed merely to make the effect perceptible. The effect, as Faraday somewhat poetically put it, amounted to the "illumination of lines of force." The emphasis had shifted subtly from the condition of the particles of the heavy glass to the peculiar nature of the magnetic line of force.

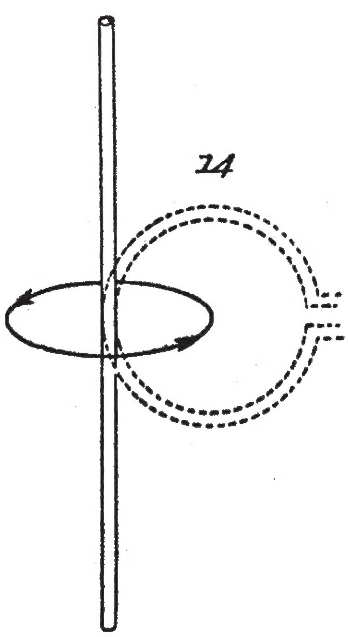

Fig. 3. Faraday's illustration of the "polar" nature of the circular line of force. When the current-carrying wire is bent into a circle, the line of force enters on one side and exits on the other side of the plane of the circle. The lines of force will be crowded together within the circle and dispersed outside it, giving the appearance of polarity. If the circle is repeated many times (that is, if there is a helix) the "polarity" will become obtrusive.

Diamagnetics and Paramagnetics

Before he could investigate the nature of the magnetic line of force, however, Faraday realized that he had opened a way into a new territory. If the heavy glass served to illuminate the line of force, it could not be indifferent, as a body, to the magnetic force itself. When the glass was freely suspended in the intense magnetic field between the poles of the Royal Institution's powerful electromagnet, it moved as if it were trying to escape from the field. Its long axis also turned perpendicular to the lines of magnetic force. The action of the glass was precisely opposite to the action of a bar of iron. All bodies, Faraday now found, reacted to the magnet either as the glass did or as an iron bar would. The two classes of bodies were christened diamagnetics and paramagnetics, and the science of magnetism was now extended to include all matter.

It was one thing to classify, it was another to understand. To most of Faraday's contemporaries, the problem did not appear a difficult one to solve. Since the action of diamagnetics was opposite to the action of paramagnetics, it seemed to follow that the polarity of diamagnetics must simply be opposite to that of paramagnetics. If one accepted Ampère's theory of magnetism, this meant that somehow the currents circulating around the ultimate molecules of diamagnetics and those circulating around the molecules of paramagnetics must be moving in opposite directions. Both Edmond Becquerel and Wilhelm Weber adopted modifications of this theory and insisted upon its necessary consequence—that diamagnetic polarity was simply the opposite of paramagnetic polarity.

Faraday, who had never accepted Ampère's physical model, was not so sure. His doubts led him to seek experimental evidence of diamagnetic polarity unrelentingly for 5 years, but to no avail. The polarity was *not* in the particles but was in the line of force. From 1850 on, Faraday shifted the focus of his attention from the manifestations of force in matter to the line of force in space itself. In many ways these last researches were to be the subtlest and most abstract and fundamental of them all. Out of them were to come the foundations of classical field theory.

The magnetic line of force differed from the electrostatic in two important respects. The electrostatic line of force depended upon molecular strains for its propagation, so it always had "ends." These were, so to speak, the "poles" which could be labeled positive and negative. The electrostatic line of force, then, could never originate and terminate upon the same conducting body. But this was precisely what the magnetic line of force did. The mag-

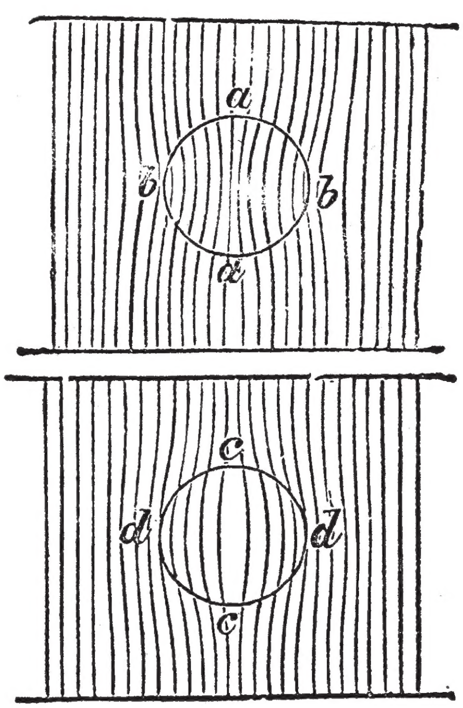

Fig. 4. Diagrammatic representations of a paramagnetic substance (top) and a diamagnetic substance (bottom) in a uniform magnetic field. The "polarity" of the paramagnetic substance is represented by the compression of the lines of force at *aa*. There is no such compression in the diamagnetic substance; *cc* does not represent polarity opposite to that at *aa*.

netic "poles," however, appeared to be perfectly arbitrary points in a homogeneous bar magnet. Since there was no detectable diamagnetic polarity, might it not be possible to eliminate the poles themselves? What, then, would become of the lines of force in such a view? Must they not be continuous, closed curves which passed *through* the magnet?

In a series of brilliantly simple experiments Faraday showed this to be the case. Using the law of electromagnetic induction from his *First Series of Experimental Researches,* he showed that the number of lines of force external to the magnet was the same as the number of lines that passed through the magnet. The magnet seemingly served only to concentrate the lines of force, or, as Faraday put it, a magnet was "the habitation of lines of force."

The concentration of the lines of force in the magnet implied that the lines of force were more easily conducted through the soft iron than through the surrounding medium. It was this implication that Faraday made explicit in defining the difference between paramagnetics and diamagnetics. Paramagnetics conducted the lines of force easily, so the lines converged upon paramagnetic bodies; diamagnetic bodies were poor conductors, so the lines avoided them. Each type of body, therefore, produced characteristic patterns of lines of force. It was by using these patterns that Faraday was able to refute those who claimed reverse paramagnetic polarity for diamagnetics. In Fig. 4 the case for the diamagnetic is *not* the reverse of the case for the paramagnetic. If poles be defined as places of maximum concentration of the lines of force, then it may be easily seen that there are no poles at all associated with the diamagnetic body.

Spatial Strain

The magnetic "conductibility" of bodies determined their para- or diamagnetic condition, but what happened when no bodies were around? Faraday had long known that the magnetic lines of force existed in the best vacuum he could obtain. Ordinary bodies merely served to concentrate or diffuse them; empty space, it appeared, could conduct them. Conduction of the line of force involved the presence of a strain, and this presence forced the question of what carried the strain in empty space. Faraday was almost alone, in the 19th century, in refusing to accept the ether as the basis for magnetic strains. The ether, it must be remembered, was considered to be atomic, and, if that were the case, it would have to exhibit the kind of polarities which Faraday had proved did not exist. He seems quietly to have adopted a phenomenalistic point of view. If there was a strain but no substance to be strained, then so be it. He had, after all, argued before that we can only know force, not substance, and if the force was manifest, then that was as far as we can go. The lines of force simply were strains. As far back as 1846 he had even suggested, in a wild speculation, that vibrations of lines of force might be light waves. Then he had quite explicitly denied the existence of the ether.

By 1855 the system was complete. Matter itself was but a peculiar kind of spatial strain with which the magnetic and electrostatic lines of force were associated. The energy of the universe was to be found in these strains. The fundamental postulate of field theory had been laid down.

Unfortunately, very few of Faraday's contemporaries were aware of the fact that a revolution was going on under their very noses. A typical reaction was that of Sir George Biddell Airy, the Astronomer Royal, who, when asked what he thought of Faraday's work on magnetism, replied (*4*), "The effect of a magnet upon another magnet may be represented *perfectly* by supposing that certain parts act just as if they pulled by a string, and that certain other parts act just as if they pushed with a stick. And the representation is not vague, but is a matter of strict numerical calculation. . . . I can hardly imagine anyone who practically and numerically knows this agreement, to hesitate an instant in the choice between this simple and precise action, on the one hand, and anything so vague and varying as lines of force, on the other hand."

One of the few who did hesitate was James Clerk Maxwell, who saw what Airy and others missed. The lines of force could be represented mathematically, they could be given all the precision that Airy demanded, and the concept of the field might lead to new and exciting discoveries. In the 1860's, as Faraday slowly sank into senility, Maxwell's eager mind began to explore the electromagnetic field. When Faraday died on 25 August 1867, Maxwell had already begun to lay the foundations for his great treatise. It would have pleased Faraday to know that his idea of the line of force was, in Maxwell's hands, to become the unifying thread in a physical system encompassing the cosmos. It was the line of force that tied all together into a *Uni*verse worthy of the God he had worshiped all his life.

References and Note

1. See L. P. Williams, *Michael Faraday, A Biography* (Basic Books, New York, 1965).
2. A. Fresnel, *Mémoires sur l'électrodynamique* (Paris, 1885–87), vol. 1, p. 144.
3. The argument is too complicated to be given here; the reader is referred to L. P. Williams (*1*, pp. 241 ff.).
4. H. Bence Jones, *The Life and Letters of Faraday* (London, 1870), vol. 2, p. 353.